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Soil salinity patterns in *Tamarix* invasions in the Bighorn Basin, Wyoming, USA

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Abstract

Saltcedar (*Tamarix* spp.) is an exotic, invasive shrub of riparian corridors in the western United States that can promote soil salinization via leaf exudates as *Tamarix* litter accumulates on the soil surface. *Tamarix* stands occur in association with big sagebrush (*Artemisia tridentata*), greasewood (*Sarcobatus vermiculatus*), and cottonwood (*Populus deltoides*) in northern Wyoming, depending on topographic position. Revegetation of *Tamarix*-invaded sites can be limited by altered soil conditions. *Tamarix* stands in northcentral Wyoming were selected to determine the relationship of *Tamarix* shrubs and associated vegetation to soil salinity, pH, and nutrients. In general, salinity of surface soils (0–5 cm) was greater and pH was lower than in deeper soils. Surface soils (0–5 cm) beneath *Tamarix* have greater salinity and lower pH than soil in interspaces. Because soil salinity in the Bighorn Basin is lower than levels documented in most *Tamarix* stands of the southwestern United States, many species used for revegetation should tolerate soil conditions here following *Tamarix* control.

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1. Introduction

Tamarix ramosissima Ledebour, *T. chinensis* Loureiro, and their hybrids are introduced shrubs that have established along North American waterways from Mexico to Montana (Robinson, 1965). *Tamarix* invasions have contributed to the reduction of native riparian habitats in the southwestern United States by replacing native species and desiccating essential wetlands (Horton, 1977; Howe and Knopf, 1991; Busch and Smith, 1995). To a lesser extent and more recently, *Tamarix* has become naturalized in northern Rocky Mountain states and is a declared noxious weed in Wyoming and Montana. The northern extent of its range reaches into western North Dakota along the Missouri River (Pearce and Smith, 2003). The spread of these species into Wyoming and Montana elicits questions regarding *Tamarix* invasiveness and influence in northern, temperate arid lands. Because northern *Tamarix* establishment is relatively recent (1950s), the impact on soil salinity may not be problematic. *Tamarix* litter and roots may alter soil organic content and nutrient availability creating islands of fertility. We examine soil characteristics of northern Wyoming *Tamarix* stands differing in native species composition to characterize patterns of soil chemistry among microsites within stands.

Tamarix withstands saline soils by regulating its salt balance via excretion of excess salts through foliar glands (Decker, 1961). Salt excretion from *Tamarix* leaves promotes salinization of soils as invasions increase in dominance (Smith et al., 1998), providing an advantage over those species susceptible to a saline environment (Tomanek and Ziegler, 1962; Shafroth et al., 1995; Glenn et al., 1998). As salinity and moisture patterns change with controlled flow regimes and *Tamarix* invasion, some native species may not successfully establish. Saline and xeric soil conditions at *Tamarix*-dominated sites often remain after the control and removal of *Tamarix*. Recovery of native vegetation in areas where saltcedar is controlled varies widely with site conditions, the native species present, and water flow regime (Barrows, 1993; Lesica and DeLuca, 2004). Because *Tamarix* infestations in the northern United States have less vigorous growth (Sexton, 2000; Lesica and Miles, 2001) and in general are more recent invasions (Lesica and Miles, 2001; Pearce and Smith, 2003) than in the southwestern United States, soil salinity may be less problematic for native vegetation recovery and revegetation efforts. In addition, altered soil fertility via litterfall and organic exudates may limit the impact of salinization beneath *Tamarix* (Lesica and DeLuca, 2004).

The influence of *Tamarix* on soil salinity, pH, and nutrient availability is largely unknown. Only one study has compared the characteristics of soil beneath *Tamarix* individuals to surrounding soils (Lesica and DeLuca, 2004) but did not evaluate impacts of native woody species on soils in these sites. Native shrub species such as *Artemisia*, *Atriplex*, and *Sarcobatus* are known to create islands of fertility and alter soil pH and electrical conductivity (EC) beneath individuals, indicating the importance of assessing spatial patterning of soil characteristics beneath shrub canopies (Roberts, 1950; Charley and West, 1975; Halvorson et al., 1997). The ability of plants to alter their edaphic environment occurs primarily

through addition of organic matter and nutrient cycling. Because northern *Tamarix* stands often have bare interspaces it is likely that islands of greater fertility may occur beneath *Tamarix*. The objective of this study is to determine vertical and horizontal spatial patterning of physiochemical soil properties within *Tamarix*-invaded sites. We define soil differences among *Tamarix*, native woody species, and bare interspace microsites to more clearly characterize potential for return of native vegetation.

2. Materials and methods

2.1. Study sites

Tamarix-invaded sites differing in topographic position and vegetative cover were examined for soil characteristics beneath *Tamarix* shrubs, in interspaces, and beneath native woody species in the Bighorn Basin, Wyoming, USA The Bighorn Basin, located in northcentral Wyoming, is drained by the Bighorn River. The basin floor is benched and terraced by water courses, while the upland areas consist of clayey hills. The Bighorn Basin has a cool temperate, semi-arid climate, low elevation relative to surrounding mountains (1170–1314 m), hot summers, and an average frost free period of 125 days (Knight et al., 1987). Temperatures average $-4\,°C$ in January and $22\,°C$ in July (Martner, 1986). Spring and early summer rainfall accounts for two-thirds of the 17.8 cm annual precipitation; the balance falls as snow (Martner, 1986).

The research sites were located between Bighorn Lake to the north and Nowater Creek to the south. The floodplains surrounding Bighorn Lake have undergone significant changes in the last 50 years. Due to Bighorn River regulation, fire, agricultural practices, and *Tamarix* establishment, there has been a shift from woodlands to shrublands (Akashi, 1988). *P. deltoides* mortality and lack of recruitment coupled with *Tamarix* establishment has promoted the conversion of woodlands to shrublands. Further, the formation of Bighorn Lake provided vast areas of saturated soil for *Tamarix* recruitment. Until 1954, shrublands in the study area were likely dominated by *Sarcobatus vermiculatus* and *Rhus trilobata*, but the mid-60s witnessed the conversion of these areas to *Tamarix*-associated shrublands (Akashi, 1988). By 1986 it is estimated that the area of *Tamarix*-associated shrublands surpassed native shrublands near Bighorn Lake (Akashi, 1988). The high density and cover of *Tamarix* in the study sites near Bighorn Lake along with low densities of native woody species indicate the need for *Tamarix* removal and reestablishment of native species (Table 1).

A change in plant communities of the Bighorn Basin is evident as one proceeds from the basin floor to higher topographic positions (Knight, 1994). We selected four invaded stand types varying in topographic position for study: (1) sagebrush steppe; (2) greasewood floodplain; (3) mature cottonwood floodplain; and (4) cottonwood recruitment drainages (Fig. 1). Four replicate sites (>1 ha) of each stand type varying in *Tamarix* dominance were selected for study (16 sites) in 2002. Two dams

Table 1
Vegetative characteristics of sagebrush steppe, greasewood floodplain, mature cottonwood floodplain, and cottonwood recruitment sites invaded by Tamarix spp. in the Bighorn Basin, Wyoming, USA

| Stand type | Tamarix characteristics | | | Native woody species | Annual production | | Cover (%) | | | | |
	Density (shrub/m²)	Height (m)	Canopy diameter (m)	Density (no./m²)	Natives kg/ha	Exotics kg/ha	Tamarix	Native shrub	Forb & grass	Litter	Bare-ground
Sagebrush steppe	0.47 (0.02–1.4)[a]	1.6 (0.1–4.3)	1.6 (0.1–5.1)	0.14	80	49	12 (1–19)	2 (2–3)	13 (2–19)	35 (14–60)	50 (34–64)
Greasewood floodplain	0.68 (0.4–0.9)	1.9 (0.2–5.3)	1.2 (0.2–5.2)	0.07	23	30	44 (47–67)	5 (0–10)	5 (1–11)	81 (69–90)	16 (7–27)
Mature cottonwood floodplain	0.32 (0.1–0.5)	1.8 (0.4–3.3)	1.1 (0.2–3.2)	0.18	134	200	15 (6–27)	1 (0–4)	23 (19–26)	80 (73–89)	3 (0.2–8)
Cottonwood recruitment drainages	0.09 (0.02–0.2)	1.4 (0.3–3.1)	0.9 (0.1–2.7)	0.56	97	59	5 (1–9)	4 (1–8)	12 (6–19)	18 (10–26)	69 (56–75)

[a] Range of values.
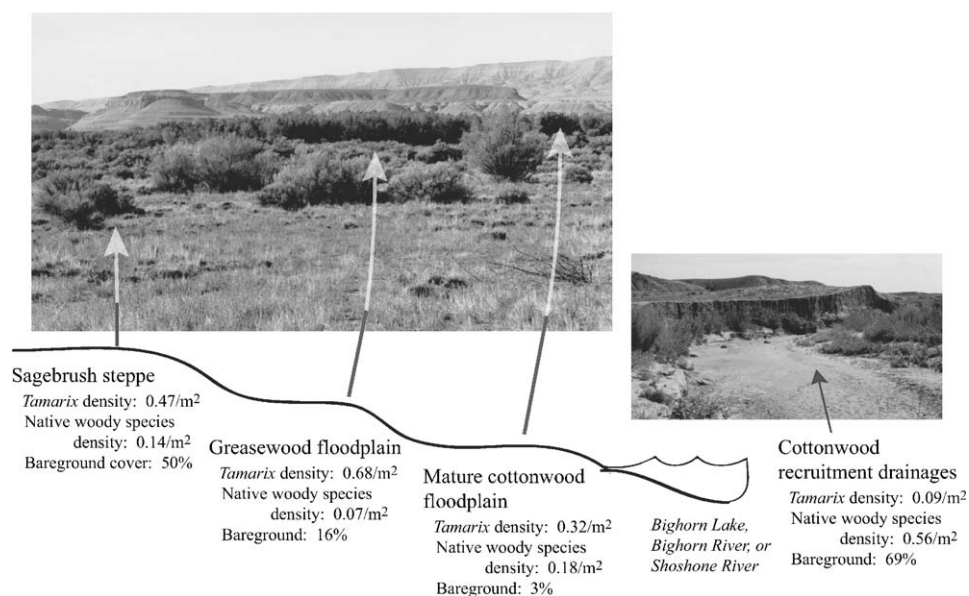
Fig. 1. Relative topographic positions of four stand types selected for study in 2002 in the Bighorn Basin of northern Wyoming, USA Cottonwood recruitment sites were located along drainages flowing into the Bighorn River and were not adjacent to Bighorn Lake.

in the Bighorn River drainage influence water flows. The Boysen Dam, located upstream from the study sites on the Wind River, creates Boysen Reservoir. The Wind River is renamed Bighorn River just south of Thermopolis, Wyoming. The Yellowtail Dam (1966), located downstream from the study sites on the Bighorn River in southcentral Montana, creates Bighorn Lake. The majority of sites located in the sagebrush steppe and greasewood floodplain are influenced by Bighorn Lake flooding events. Two sites located in sagebrush steppe likely established on abandoned farmland and are not influenced by Bighorn Lake fluctuations. Mature cottonwood floodplain sites are influenced by Bighorn River and Shoshone River fluctuations, and because of their proximity to Bighorn Lake, are also influenced by lake levels. Since the construction of Boysen Dam (1952), flooding frequency of Bighorn River has decreased from once in 2.5 years to once in 10 years (Akashi, 1988). Most recent flood levels occurred in 1997 and 1999 and all research sites but two near Bighorn Lake were inundated. Our cottonwood recruitment sites were selected along non-regulated drainages flowing into Bighorn River, approximately 60–110 km from Bighorn Lake, because cottonwood recruitment seldom occurs along the regulated Bighorn River. Sagebrush steppe soils are coarse-loamy, mixed, mesic Haplargids. Greasewood floodplain sites occur on fine-loamy and coarse-loamy, mixed, mesic Typic Torriorthents. Soils in mature cottonwood floodplain and cottonwood recruitment sites are fine-loamy and coarse-loamy, respectively, mixed, mesic Typic Torrifluvents.

Exotic species made considerable contributions to herbaceous production, especially in the greasewood and mature cottonwood floodplain sites (Table 1). Herbaceous vegetation in sagebrush steppe sites was predominantly *Sporobolus airoides* (Torr.) Torr. and the exotic species *Salsola iberica* Sennen and Pau and *Halogeton glomeratus* (M. Bieb.) C.A. Meyer. Greasewood floodplain sites were dominated by weedy species (*Iva axillaris* Pursh, *Cardaria pubescens* (C. A. Meyer) Jarmolenko, *Centaurea repens* L., *H. glomeratus*, *S. iberica*). *Glycyrrhiza lepidota* Pursh., *Agropyron trachycaulum* (Link) Malte, and *Hordeum jubatum* L. were the predominant herbaceous species in mature cottonwood floodplain sites. A variety of exotic (*S. iberica*, *C. repens*, *Bromus tectorum* L.) and native (*Psoralea lanceolata* Pursh., *Oryzopsis hymenoides* (R. & S.) Ricker, *Elymus canadensis* L.) species dominated cottonwood recruitment sites (more detailed vegetative descriptions are available in Ladenburger, 2003). Mature cottonwood floodplain sites had greatest annual herbaceous production of the four stand types sampled (Table 1), the majority from the exotic Russian knapweed (*C. repens*) on our most productive site which lacked cottonwood cover and had a high density of large *Tamarix* shrubs.

Tamarix cover and density was greatest and native woody species density the least in the greasewood floodplain (Table 1). High *Tamarix* density over all sagebrush steppe sites resulted from an uncommonly great establishment of young individuals at one of the four sites. Discounting one outlier site, *Tamarix* shrubs were largest at sagebrush steppe sites and smallest at cottonwood recruitment sites where cottonwood density was high. In sagebrush steppe, greasewood floodplain, and mature cottonwood floodplain sites, *Tamarix* density was greater than densities of all other woody species. *Artemisia tridentata* and *Chrysothamnus* species were the native woody species of the sagebrush steppe. *S. vermiculatus*, *A. tridentata*, and *Chrysothamnus* species were woody natives present at the greasewood floodplain sites. Woody species at mature cottonwood floodplain sites were *P. deltoides*, *Symphoricarpos occidentalis*, *Shepherdia canadensis*, *Rosa woodsii*, and the exotic *Elaeagnus angustifolia*. *Tamarix* size, density, and cover were least and native woody plant density greatest in the cottonwood recruitment drainages. Cottonwood recruitment sites contained *Salix exigua* and *Artemisia cana* in addition to the *P. deltoides*, *A.tridentata*, *Chrysothamnus* spp., and *S. vermiculatus* found in other stand types.

2.2. Soil sampling

Within each site, microsite positions were sampled to determine vertical and horizontal physio-chemical soil patterns present. At each of the 16 sites, we sampled five replicates of five microsite positions: (1) beneath the canopy of large-based *Tamarix*, (2) interspaces of the large-based *Tamarix*, (3) beneath the canopy of randomly selected *Tamarix*, (4) interspaces of the randomly selected *Tamarix*, and (5) beneath the canopy of native woody species. At each site, *Tamarix* with the largest basal sizes were subjectively selected for that microsite while random *Tamarix* were selected through random compass direction and random number of paces from the site's center. Within each microsite position, soil cores (7.5 cm diameter) were

taken from four soil depths (0–5, 5–20, 20–35, and 35–50 cm increments), resulting in a total of 1600 samples (16 sites × 5 microsites × 5 replicates × 4 depths). Soil samples were air dried and sieved to obtain the ⩽ 2 mm fraction.

2.3. Soil testing

EC and pH were determined for all soil samples using the 1:1 soil mass to water volume method (Soil and Plant Analysis Council, 2000). A subset of soil samples from sagebrush steppe, greasewood floodplain, and mature cottonwood floodplain sites (two from the large-based *Tamarix* and two from the random *Tamarix* microsites in the 0–5 and 5–20 cm depths) were randomly selected for additional soil analysis to document texture (hydrometer method; Gee and Bauder, 1986), organic matter (Walkley-Black method; Nelson and Sommers, 1982), and plant available phosphate (sodium bicarbonate method; Olsen and Sommers, 1982), nitrate (chromotropic acid method; Sims and Jackson, 1971), and potassium (ammonium bicarbonate-DTPA extraction; Soltanpour and Schwab, 1977). Composite samples of soil from beneath native species (0–5 and 5–20 cm) and composite samples of interspace soil (0–5 and 5–20 cm) were also analyzed for texture, organic matter (%), and plant available phosphate, nitrate, and potassium. In cottonwood recruitment drainages, only composite samples of interspace soil (0–5 and 5–20 cm) were selected for additional analysis.

2.4. Experimental design and data analysis

Within each stand type, soil data were assessed using analysis of variance appropriate to a split plot randomized complete block design to determine soil differences among microsite positions (main plot) and soil depths (subplots). The four sites within each stand type were treated as replicate blocks. We consider blocks (stand type replicates) and microsite treatments as random effects and soil depth treatments as fixed effects and follow procedures of a mixed model (Milliken and Johnson, 1984). Data were assessed and do conform to assumptions of normality (Shapiro and Wilk, 1965) and sphericity (Mauchley, 1940). Analyses were performed using JMP statistical software (SAS Institute Inc., 2000). Where significant treatment differences occurred, mean separation was conducted using Fisher's protected least significant difference (FLSD, $\alpha = 0.05$).

3. Results

3.1. Soil patterns within sagebrush steppe sites

Within sagebrush steppe sites, soil EC, pH, organic matter, nitrate, and phosphate differed among microsites depending on soil depth. At the surface (0–5 cm), soil EC was greater beneath large-based *Tamarix* than in other microsites and least in bare interspaces (microsite ∗ soil depth interaction: $p = 0.0147$, Fig. 2a). Surface soil EC
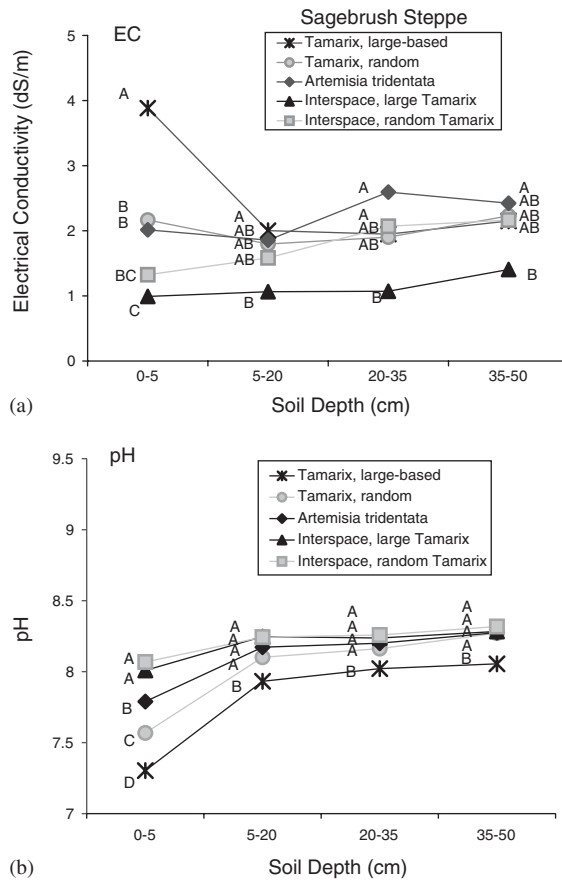
Fig. 2. Soil EC (a) and pH levels (b) at five microsite positions within sagebrush steppe sites invaded by *Tamarix* spp. in the Bighorn Basin, Wyoming, USA. Within a soil depth, microsite means with the same letter do not differ ($p > 0.05$, FLSD).

was greater under sagebrush (*A. tridentata*) and random *Tamarix* shrubs than interspaces. Microsite EC differed less in the deeper soil layers, although interspaces between large-based *Tamarix* had lowest EC values at all soil depths. In the surface soils (0–5 cm), pH was greater in interspaces than other microsites and least beneath *Tamarix* (microsite * soil depth interaction: $p = 0.0017$, Fig. 2b). Within deeper soil layers, pH levels were lower beneath large-based *Tamarix* than in other microsites. Organic matter, nitrate, and phosphate levels were greater in the 0–5 cm soil depth beneath large-based *Tamarix* than all other microsites (microsite * soil depth interaction for organic matter: $p < 0.0001$, nitrate: $p = 0.0117$, phosphate: $p = 0.0007$; Table 2). Irrespective of soil depth, potassium levels did not differ among microsites, but were greater at the soil surface than deeper soil layers (Table 2). Soil texture generally consisted of sandy loams in the sagebrush steppe sites (Ladenburger, 2003).

3.2. Soil patterns within greasewood floodplain sites

Greasewood floodplain sites had the highest soil EC levels in the study and EC differed among microsites by soil depth (microsite $*$ soil depth interaction: $p = 0.0457$). EC was greatest beneath the greasewood (*S. vermiculatus*) and large-based *Tamarix* in surface soils (0–5 cm), but EC did not differ among microsites within deeper soil layers (Fig. 3a). Soil pH was least beneath *Tamarix* and greatest beneath greasewood in surface soils (microsite $*$ soil depth interaction: $p < 0.0001$, Fig. 3b). At the 5–20 cm soil depth, pH remained greater beneath the greasewood than in all other microsites, but did not differ among microsites in deeper soils (20–35 and 35–50 cm). Organic matter levels in the 0–5 cm soil depth were greater beneath the large-based and random *Tamarix* than in the interspaces or beneath greasewood (microsite $*$ soil depth interaction: $p = 0.0427$, Table 2). Nitrate levels beneath the greasewood and large-based *Tamarix* did not differ but levels beneath greasewood were greater than beneath random *Tamarix* and interspace microsites. (microsite: $p = 0.0319$). Irrespective of soil microsites, nitrate, phosphate, and potassium levels were greater in the 0–5 cm soil depth than the 5–20 cm depth (Table 2). Soil textures ranged from loamy sand to clay loams. Within a site, textures were consistent among samples.

3.3. Soil patterns within mature cottonwood floodplain sites

Soil EC and pH in mature cottonwood floodplain sites did not differ among microsites, regardless of soil depth (EC microsite: $p = 0.2649$; EC soil depth: $p = 0.8806$; pH microsite: $p = 0.2306$; Fig. 4a and b). Soil pH differed among soil depths when averaged across microsites (pH soil depth: $p < 0.0001$). Soil pH was lower in the surface soils (0–5 cm) than all other depths. Soil pH in the 5–20 cm soil depth was lower than the 20–35 and 35–50 cm depths. Organic matter, nitrate, phosphate, and potassium levels in the soil surface (0–5 cm) were greater than levels in deeper soils (5–20 cm) (Table 2). In general, more clay was present in mature cottonwood floodplain soils than the other stand types.

3.4. Soil patterns within cottonwood recruitment drainages

Cottonwood recruitment sites were primarily sandy loam soils with much less silt and clay content than mature cottonwood sites. Soil beneath the large-based *Tamarix* had higher EC levels than beneath cottonwood (*P. deltoides*) and interspace microsites when averaged across soil depths (microsite: $p = 0.0191$, Fig. 5a). Further, EC was greatest in surface soils (0–5 cm) when averaged across microsites (soil depth: $p < 0.0001$). However, average soil EC levels were below $1\,\mathrm{dS\,m^{-1}}$ for all microsites and depths in the cottonwood recruitment sites. Soil pH was lower beneath large-based *Tamarix* than in all other microsites throughout each of the four sampling depths (microsite $*$ soil depth interaction: $p = 0.0057$, Fig. 5b). Within surface soils, pH was lower beneath the randomly selected *Tamarix* than in the cottonwood and interspace microsites. Organic matter, nitrate, phosphate, and potassium content did not differ between soil depths (Table 2).

Table 2
Soil organic matter and nutrients in sagebrush steppe, greasewood floodplain, mature cottonwood floodplain, and cottonwood recruitment sites invaded by *Tamarix* spp. in the Bighorn Basin, Wyoming, USA

Stand type Soil texture (class)	Soil depth (cm)	Microsite[a]	OM (%)	NO$_3$ (mg/kg)	PO$_4$ (mg/kg)	K (mg/kg)
Sagebrush steppe Sandy loam and loam	0–5	*Tamarix*, large-based	5.6 ± 0.5a	134.4 ± 37.1a	73.8 ± 9.6a	627.3 ± 82.9 ⎫
		Tamarix, random	1.8 ± 0.3b	32.4 ± 15.1b	25.0 ± 5.7bc	484.8 ± 128.9 ⎬ A
		Artemisia tridentata	2.1 ± 0.2b	21.0 ± 6.1b	27.5 ± 3.6b	490.5 ± 60.2 ⎪
		Interspace	1.2 ± 0.2b	13.0 ± 4.0b	18.5 ± 2.2c	338.0 ± 42.3 ⎭
	5–20	*Tamarix*, large-based	1.1 ± 0.1a	14.6 ± 4.5a	11.5 ± 1.8a	442.3 ± 73.4 ⎫
		Tamarix, random	1.0 ± 0.2a	4.5 ± 2.5a	5.3 ± 0.8a	243.5 ± 22.8 ⎬ B
		Artemisia tridentata	1.0 ± 0.1a	3.5 ± 0.3a	7.0 ± 1.3a	255.0 ± 56.4 ⎪
		Interspace	0.9 ± 0.1a	5.5 ± 1.4a	6.0 ± 0.8a	220.0 ± 27.2 ⎭
Greasewood floodplain Sandy loam, loamy sand, loam, and clay loam	0–5	*Tamarix*, large-based	5.8 ± 1.1a	76.3 ± 31.8 ⎫	53.5 ± 16.4 ⎫	729.8 ± 200.8 ⎫
		Tamarix, random	3.9 ± 0.7b	22.1 ± 4.9 ⎬ A	23.5 ± 2.5 ⎬ A	383.5 ± 50.6 ⎬ A
		Sarcobatus vermiculatus	3.1 ± 1.0c	92.8 ± 25.3 ⎪	44.0 ± 2.9 ⎪	782.0 ± 80.4 ⎪
		Interspace	2.6 ± 0.3c	24.8 ± 8.6 ⎭	29.0 ± 3.9 ⎭	378.0 ± 56.9 ⎭
	5–20	*Tamarix*, large-based	1.8 ± 0.4a	16.5 ± 5.6 ⎫	23.5 ± 4.1 ⎫	533.8 ± 93.5 ⎫
		Tamarix, random	1.4 ± 0.3a	5.9 ± 2.9 ⎬ B	11.5 ± 1.1 ⎬ B	277.0 ± 29.8 ⎬ B
		Sarcobatus vermiculatus	1.9 ± 0.8a	25.5 ± 7.8 ⎪	23.5 ± 1.5 ⎪	507.0 ± 52.2 ⎪
		Interspace	1.5 ± 0.4a	8.5 ± 2.6 ⎭	15.0 ± 2.4 ⎭	328.5 ± 41.1 ⎭

Soil / Microsite[a]	Depth (cm)				
Mature cottonwood floodplain Silty loam, silty clay loam, silty clay loam and clay loam	0–5				
Tamarix, large-based		8.6 ± 1.1 ⎫	35.3 ± 10.2 ⎫	27.8 ± 3.5 ⎫	690.3 ± 179.2 ⎫
Tamarix, random		6.5 ± 1.1 ⎭ A	15.9 ± 4.1 ⎭ A	36.5 ± 5.3 ⎪	585.8 ± 123.6 ⎪
Populus deltoides		4.8 ± 1.2 ⎫	11.7 ± 3.8 ⎫	22.7 ± 2.4 ⎬ A	386.0 ± 44.0 ⎬ A
Interspace		5.5 ± 0.7 ⎭ B	17.8 ± 2.9 ⎭ B	30.0 ± 3.4 ⎭	516.0 ± 63.2 ⎭
Tamarix, large-based	5–20	1.8 ± 0.2 ⎫	2.1 ± 0.5 ⎫	13.0 ± 4.5 ⎫	426.3 ± 53.5 ⎫
Tamarix, random		2.3 ± 0.4 ⎪	1.8 ± 0.3 ⎪	14.8 ± 3.3 ⎬ B	423.3 ± 55.2 ⎬ B
Populus deltoides		1.9 ± 0.3 ⎬ B	1.0 ± 0.0 ⎬ B	11.3 ± 1.3 ⎪	330.0 ± 17.5 ⎪
Interspace		2.1 ± 0.3 ⎭	1.5 ± 0.3 ⎭	12.5 ± 2.6 ⎭	336.5 ± 29.0 ⎭
Cottonwood recruitment drainages Sandy loam, loam, and loamy sand					
Interspace	0–5	0.7 ± 0.3 A	8.5 ± 4.9 A	7.5 ± 4.8 A	142.0 ± 49.7 A
Interspace	5–20	0.4 ± 0.1 A	3.5 ± 1.0 A	1.0 ± 0.5 A	90.0 ± 12.8 A

Lower case letters compare microsite soil parameter means within a soil depth. Uppercase letters compare soil depths within a soil parameter and averaged across microsites. Means with the same letter do not differ ($P > 0.05$, FLSD).

[a] Microsite samples obtained beneath the canopy of listed woody species and interspaces.
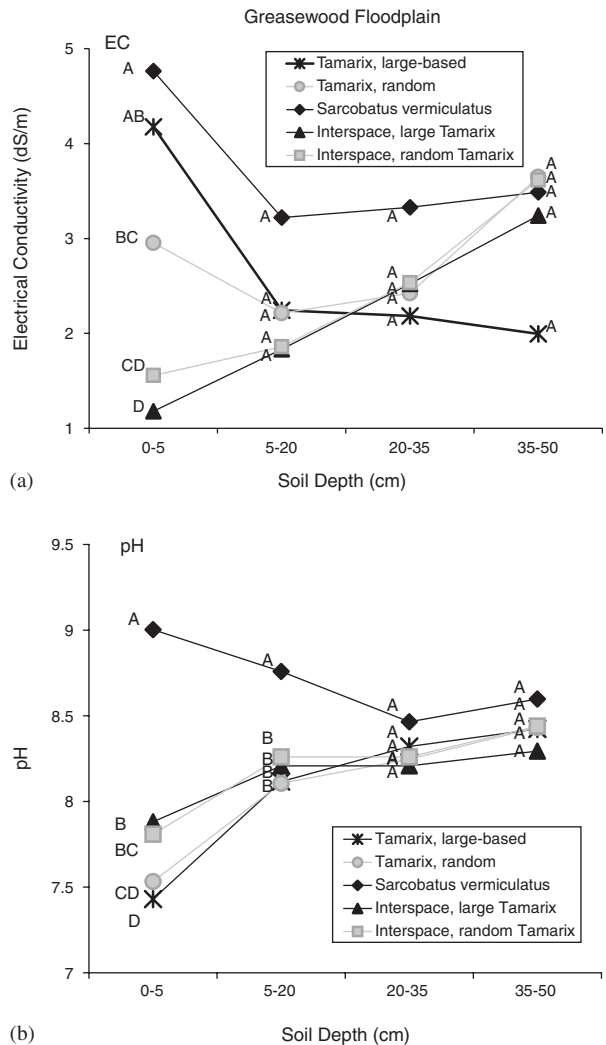
Fig. 3. Soil EC (a) and pH levels (b) at five microsite positions within greasewood floodplain sites invaded by *Tamarix* spp. in the Bighorn Basin, Wyoming, USA. Within a soil depth, microsite means with the same letter do not differ ($p > 0.05$, FLSD).

4. Discussion

Spatial patterns of soil chemical properties were evident in the four stand types examined in this study. Clearly, *Tamarix*, especially large plants, impact soil conditions directly beneath their canopies in a manner comparable to native shrubs in arid upland sites. Similarly, soil EC and inorganic nitrogen beneath *Tamarix* canopies in northeastern Montana was higher and pH was lower relative to soils
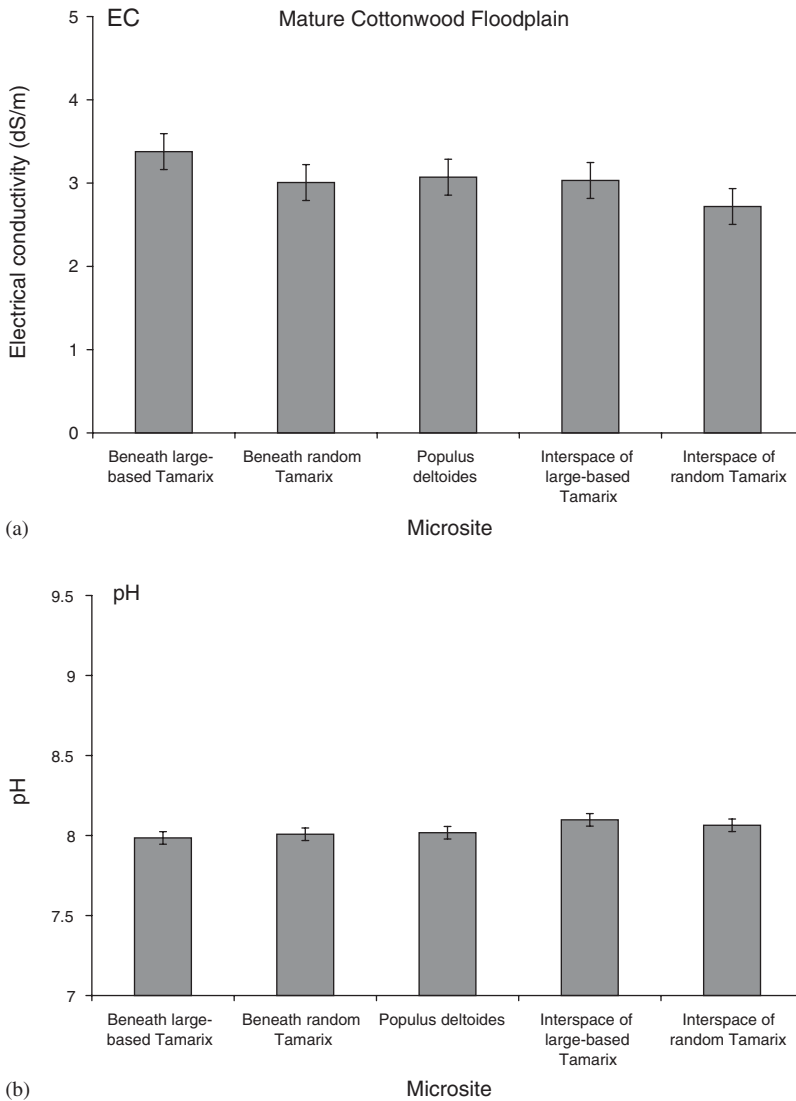
Fig. 4. Soil EC (a) and pH levels (b) at five microsite positions within mature cottonwood floodplain sites invaded by *Tamarix* spp. in the Bighorn Basin, Wyoming, USA. Microsite values are means across soil depths and did not differ; $p > 0.05$, *F*-test.

beneath grasses (Lesica and DeLuca, 2004). The increased salinity and nutrients beneath large *Tamarix* is probably the result of litter fall and reduced occurrence of flooding events.

　　The highest salinity levels were documented in the surface soils of the greasewood floodplain probably because of the presence of greasewood and larger *Tamarix*
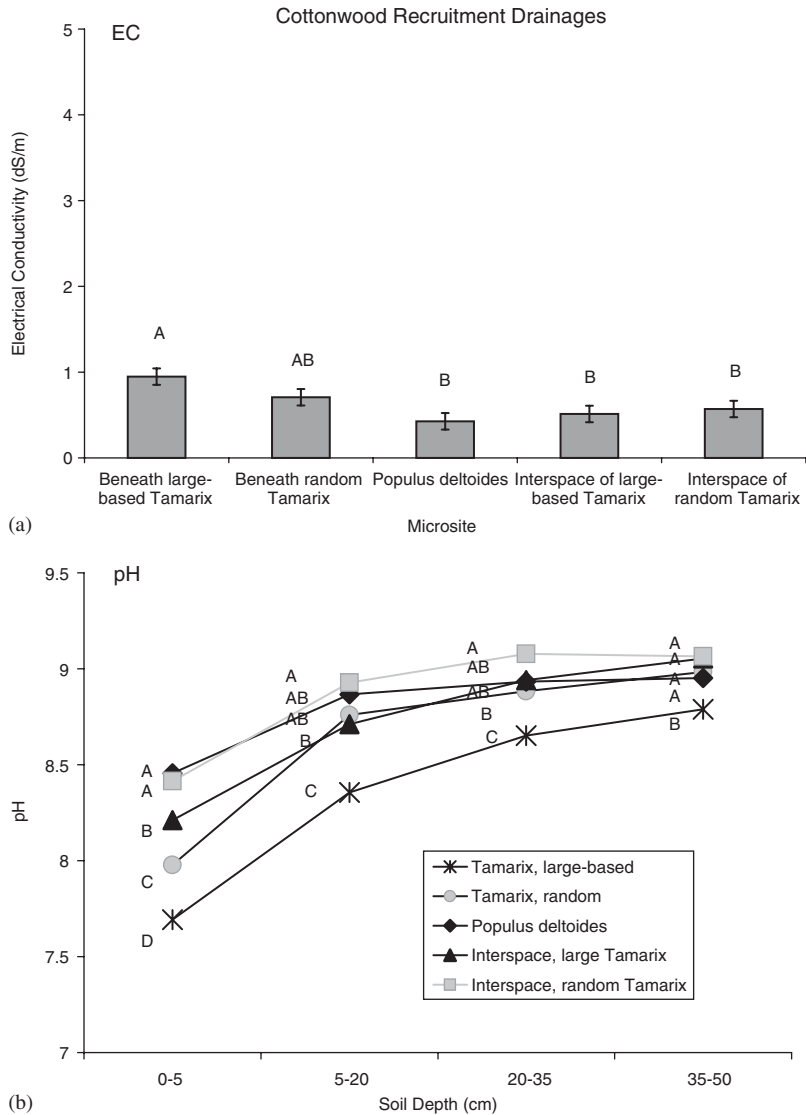
Fig. 5. Soil EC (a) and pH levels (b) at five microsite positions within cottonwood recruitment sites invaded by *Tamarix* spp. in the Bighorn Basin, Wyoming, USA. EC microsite means with the same letter do not differ (means are of four soil depths; $p > 0.05$, FLSD). Within a soil depth, pH microsite means with the same letter do not differ ($p > 0.05$, FLSD).

shrubs. In sagebrush steppe sites, elevated salinity in surface soils is likely due to the presence of larger *Tamarix* shrubs and a lack of recent leaching events at two of these sites. The lowest salinity levels were documented in the cottonwood recruitment drainages, supporting the postulate that flushing flows in these drainages reduce salt

accumulations. Lower soil pH beneath *Tamarix* may result from increased organic acids after breakdown of accumulated litter and deposition of soluble salts. Increased microbial respiration due to the accumulated litter may contribute to decreased pH. Soluble salts, in the absence of high levels of exchangeable sodium, can also decrease the pH in these generally alkaline soils. In the mature cottonwood floodplain, lack of microsite differences in EC and pH may be due to flooding events of Bighorn Lake (1997, 1999). Extended periods of high water would leach salts and nutrients and dissipate microsite effects.

Comparable to our study, *Tamarix* stands (17–22 years old) in northeastern Montana had soil EC averaging twice as high beneath *Tamarix* than in the interspaces, but salinity was at a level tolerable to most range plants (Lesica and DeLuca, 2004). Other studies find little differences when comparing soil salinity within stands of *Tamarix* and native vegetation (Campbell and Dick-Peddie, 1964; Stromberg, 1998; Sexton, 2000). Sexton's (2000) results parallel our documentation of lower soil pH below *Tamarix*; however, he did not document higher EC levels in *Tamarix* stands. Sexton's study included random soil sampling within stand plots and sample pooling, and consequently did not document microsite effects. Soil salinity of southwestern United States *Tamarix* stands is generally higher than levels documented in our study. In *Tamarix* stands of northcentral Utah, Carman and Brotherson (1982) documented EC levels as high as $15\,\mathrm{dS\,m^{-1}}$ and a mean of $5.2\,\mathrm{dS\,m^{-1}}$ (0–20 cm). EC levels along the Colorado River were $12.8\,\mathrm{dS\,m^{-1}}$ to a soil depth of 90 cm (Busch and Smith, 1995). In Arizona, *Tamarix* stands less than 44 years old had maximum and mean EC levels of 5.7 and $1.5\,\mathrm{dS\,m^{-1}}$ along the San Pedro River in the 0–15 cm soil layer (Stromberg, 1998). These values are lower than those documented in our riparian sites.

After *Tamarix* control, saline, xeric soil conditions can be detrimental to the recovery of native species (Barrows, 1993). Because our EC levels were generally less than those documented in more southern distributions, native reestablishment may be less problematic after control of northern *Tamarix*. Additionally, concomitant increases in limiting nutrients may mitigate any negative effect of soil salinity (Lesica and DeLuca, 2004). Differences in soil salinity between southwestern United States *Tamarix* stands and our sites indicate that the age of invasion may influence soil salinity. *Tamarix* entered the Bighorn Basin later (1950s) (Akashi, 1988) than most *Tamarix* invasions in the southwestern United States (late 1800s and early 1900s). Soil spatial patterns may be an important determinant of native species recovery. Within sagebrush steppe and greasewood floodplain sites, islands of elevated salinity at the soil surface beneath large-based *Tamarix* and greasewood could reduce seed germination. In the sagebrush steppe, low-density *Tamarix* invasions allow native plants to grow in the shrub interspaces. Big sagebrush can establish in soils at ECs as high as $6\,\mathrm{dS\,m^{-1}}$ (Swift, 1997). *Tamarix* invasions in the Bighorn Basin may require extensive revegetation effort because of other exotic species that are common, such as *E. angustifolia*, *C. repens*, *C. pubescens*, *S. iberica*, and *Halogeton glomeratus*. Greasewood floodplain horizontal EC and pH gradients may be especially challenging to revegetation efforts. Sodium accumulations beneath greasewood can alter soil physio-chemical characteristics and toxic sodium levels create nutritional imbalances

and impair soil physical structure (Fireman and Hayward, 1952). It is likely that *Tamarix*-greasewood shrublands were once primarily greasewood shrublands and the control of *Tamarix* would possibly promote the return of this native species.

Even though soil salinity of mature cottonwood floodplain soils did not differ among microsites, elevated salinity levels ($3\,dS\,m^{-1}$) and high clay content are of concern for revegetation with cottonwood and willow. Taylor and McDaniel (1998) recommend low salinity ($<2\,dS\,m^{-1}$ for cottonwood and $<2.5\,dS\,m^{-1}$ for willow) and sandy soils for these native species to perform best. Long-term viability of these riparian areas depends on the future of cottonwood recruitment. Controlled flows on the Bighorn River favor *Tamarix* establishment and inhibit cottonwood recruitment. Under uncontrolled flow conditions, cottonwood seedlings may have a superior competitive ability over *Tamarix* seedlings (Sher et al., 2000). Mechanical clearing of mature *Tamarix* and the return of historic flooding regimes could promote *Populus* and *Salix* recruitment that may be detrimental to *Tamarix* establishment (Sher et al., 2002). Stromberg (2001) recommends the return of more natural stream flow regimes to replenish water tables, promote native species recruitment, flush salts, and deposit nutrients. Natural flooding disturbances of our cottonwood recruitment sites likely contribute to low soil salinity levels, lower *Tamarix* density, and higher incidence of native species.

When evaluating the need for revegetation, it is important to consider associated stand type, *Tamarix* density, native species presence, and presence of flushing flows. Because control and revegetation measures entail considerable expense we recommend field trials before attempting large-scale restoration. The best management strategy is to promote species that are tolerant of EC levels common within saltcedar invasions. Many grass species (e.g. *Agropyron* spp., *Elymus triticoides*, *S. airoides*) and shrub species (e.g. *A. tridentata*, *Prunus virginiana*, *S. canadensis*) are tolerant to the levels we documented. Capitalizing on high water years by clearing *Tamarix* before flooding may provide a substrate suitable for native species recruitment and revegetation measures. Managers should address northern *Tamarix* invasions immediately while soil salinities are low. Quick response to new invasions while limiting mature invasions is important for the recovery of essential habitats in the Bighorn Basin of Wyoming.

Acknowledgements

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